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14. ABSTRACT
The goal of this project was to understand microcavitation for surface cleaning. Acoustic microcavitation is brought about by low megahertz frequencies and involves micron size bubbles that last a few microseconds. During microcavitation the imploding cavities deposit large amounts of energy at the implosion sites. Microcavitation created high energy density at implosion points is effective only at the thin surface layer and therefore suitable for cleaning surfaces—a point of use deployment of energy enhances efficiency. The crucial question this research has explored is whether it is possible to scale up microcavitation assisted surface cleaning to achieve higher surface cleaning rates. Further, for external surface cleaning, we investigated the possibility of combining microcavitation cleaning with moderated water-jet cleaning.

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Surface removal, coating removal, microcavitation

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Introduction

Microcavitation for Surface Cleaning

The primary objective of this research was to explore a new ACIM method–acoustic coaxing induced microcavitation–to solve the problem of removing paint-rust-scales from surfaces e.g. ship surfaces and pipe interiors. ACIM is a new method for constructively controlling microcavitation. This microcavitation based cleaning was to be accomplished using only "silent sound and clean water". No chemicals were be used.

SURFACE CLEANING USING ACIM

Acoustic microcavitation invariably results in energy concentration, though its occurrence ordinarily is unpredictable and uncontrollable. Acoustic Microcavitation at low megahertz frequencies in a water like host involves micron size bubbles that live a few microseconds. During inertial microcavitation the imploding bubbles are known to deposit immense energy over very short length scales: "...five atmosphere sound wave at a frequency of 3 MHz can cause a bubble with an initial radius of 1 μm to grow to a radius of 3 μm. This nearly empty gas bubble will collapse in about 0.3 μs depositing into a fraction of a cubic micron ...over 100 MeV[of energy]." (Apfel, 1997). It stands to reason then that if the microcavitation bubbles were to implode singly, or in small clusters, the effects of implosion would be localized and not felt far from the implosion site. That is, if the location where inertial microcavitation occurs is controlled then it would be possible to remove even micron size material with surgical precision, rendering the surface of a substrate entirely undamaged. The important characteristics of ACIM are the following:

1. ACIM is energy efficient through its point of use application.
2. Intense energy density at points effect material removal in the shallow vicinity of the point, leaving the substrate wholly unaffected.
3. ACIM effects surface removal independent of the nature of the surface material: paint, rust or scales.
4. ACIM is environmentally responsible. No chemicals are needed. Only silent sound and clean water are used.

Because microcavitation is effective in a thin-film region of a surface, it should in principle be efficient in bringing about controlled surface erosion to remove paint, rust, and scales from surfaces.

RESEARCH

Our three research priorities were the following:

- The first goal of this research effort was to characterize the performance of microcavitation assisted surface cleaning using ACIM fields. In particular we wanted to know if there are any limitations—nature of the paint, rust or surface scales to be removed, or the geometry of the component surface to be cleaned, access to the cleaning surface, etc.—imposed on the effectiveness of microcavitation implemented surface cleaning.
- Secondly, we wanted to assess the scale-up feasibility of the ACIM process in the context of surface cleaning.
- Thirdly, we wanted to establish quantitative comparisons of the two techniques of surface cleaning: water-jetting and microcavitation, and explore their possible synthesis.

This research was primarily experimental and most tests were conducted on laboratory scale configurations. Following our experience with the ACIM research thus far, we designed suitable test set-ups, built and calibrated several different ACIM field generators and powering units, and tested variously prepared samples. Essentially, we setup ACIM fields in a tanks of clean water, locate the sample to be cleaned at a specific point in the ACIM field and observe the surface cleaning as a function of the various attributes of the ACIM field—pulse length, shape, strength and repetition frequency. Following experimental activities and investigations was carried out:

1. Effectiveness of ACIM assisted surface cleaning on various different samples was evaluated. ACIM performance for different surfaces: different paint-scales-rusts, and different geometries of the surfaces and differing degrees of surface accessibility was measured. Performance measures in terms of power input, acoustic powers used, amount of cleaning achieved, depth of cleaning, substrate state before and after cleaning, time duration, and also rate of cleaning or the evolution of cleaning were established. First tests were conducted with stationary fields and fixed samples. Once spot cleaning was well characterized then cleaning was conducted with moving sample or moving ACIM fields.

Scaled down water-jetting system was set-up in the lab so that it could be compared with the ACIM system on similar samples. The intent was not to prove one system better than other systems, but to gain a detailed understanding of different processes with a view to seek a synergistic synthesis of these techniques in designing an effective universal cleaning tool.

2. ACIM was tested for relevant scale-up. Design analysis was completed for ACIM cleaning system to clean a 1 in sq. area at a time. Using two ACIM units in close proximity performance was tested to see whether they could operate essentially independently of each other. They were found to operated essentially independently and undisturbed by the presence of the other unit in close proximity. Because two proximal units performed unaffected by each others presence it leads one to conceivably use many small units in array formation for scaled up implementation.

   ACIM fields were fully calibrated to account for the ACIM mechanism in surface removal. The sequence of cleaning or material removal from within the focal spot were studied. Studying the evolution of how a surface cleans when exposed to ACIM field was crucial in understanding microcavitation induced surface erosion and consequently helping in developing ACIM to be a viable technology.

3. Experiment with ACIM-jet mode. Not using very high speed jets, initially we studied both the annular and tandem configurations. More work was done on the tandem configuration because the first transducers we had built for the annular configurations were not very effective and procuring a second set of specialized transducer had gotten considerably delayed at the manufacturer. (That work will be continued post the project duration.) Analytically we have evaluated the effectiveness of ACIM in the convecting jet. All ACIM studies in item 1. were conducted by keeping the sample immersed in a tank of water.

DELIVERABLES

- Evaluation and understanding of microcavitation for surface cleaning.
- Scale-up assessment of microcavitation for surface cleaning.
- Setting up infrastructure of researching ACIM.

- Training and encouraging at least two graduates to be entrepreneurs willing to pursue ACIM technology.

All the above items have been well accomplished. They are briefly reported below:

- <u>Evaluation and understanding of microcavitation for surface cleaning:</u>

1. Microcavitation can be controlled for surface removal without affecting the substrate in any way. The microcavitation is effective on all kinds of coatings, however, the ease of surface removal is directly dependent on the tendency of the surface to engender cavitation, and the strength of the coating adhering to the substrate. Three different types of paints were studied though a wide variety of coated surfaces were tested. The details of the tests carried out and results are given in the two student theses arising from this work–Hang Ji, and Kevin Wanklyn. [1. Investigating Microcavitation in Bulk and on Surfaces (Feb 2002) Hang Ji; 2. A Study of Microcavitation at Surfaces (Dec 2002) Kevin Wanklyn]

2. For a given coating-substrate combination, there is a specific threshold field intensity below which no surface removal occurs. Above the threshold intensity the surface removal rate rapidly increases, however at very high intensities the rate dramatically drops because the bubble cloud of microcavitation is overwhelmingly dominant and the field effectively uncouples, i.e. cavitational implosions occur well within the liquid and away from the surface coating to be removed. For coating removal to occur it is critical that cavitation occur right on the surface. The implosive effects of cavitation drop off rapidly away from the center of implosion, within one bubble diameter or so.

3. Instead of the continuous wave insonification, pulsed insonification can be used to prevent the bubble decoupling effect at high intensities. It is found that short to moderate duty cycles of insonification are considerably more effective than continuous wave insonification.

4. Even for short duty cycles it is observed that short pulses are more effective than longer pulses. Note that a given duty cycle can be implemented with short pulses fired at high pulse repetition frequency, or long pulses with wide interpulse spacing. Surface removal is effective with short tone bursts.

Some times during cavitation the bubble fragments survive after the implosion and serve as starting nuclei for the next acoustic cycles. This condition is not satisfactory for surface removal, even though cavitation is easily facilitated. The reason is that the surviving bubble fragments cannot be guaranteed to be occurring in the immediate vicinity of the surface and hence the cavitation they generate on the following acoustic cycles may not be effective in removing surface coatings.

5. Field frequency is an important factor in determining the depth of surface removal. Smaller frequencies bring about deeper surface removal, however, very short frequencies in the low kilohertz range are associated with erratic surface removal rate. We recommend not using frequencies below 500kHz. Note that low frequency transducer systems quickly get bulky and unwieldy. Also at the other end very high frequency transducers are quite fragile and cannot be driven at high powers. A given frequency is most effectively coupled to bubbles that are at or slightly below the resonance size corresponding to that frequency. The depth of erosion is then correlated with the resonance bubble size and this provides a rough guide on which frequency to use for a given thickness of the coatings.

6. At speeds of 100 m/s water jets alone are not able to effect surface removal. However, if the water jet is combined with microcavitation, surface removal is accomplished quite efficiently.

7. It appears that microcavitation must precede water jet treatment. If an area is first exposed to water jet and then to microcavitation no additional improvement in surface removal results; the effects are the same as when microcavitation acts alone.

8. One is led to conclude that the microcavitation is effective in initiating fracture of the coatings and water jet is effective in driving the fractures unto complete peeling or detachment.

9. Optimal coating removal rate appears to be associated with 1 MHz frequency and the required water jet speed of more than 50 m/s. The combination tool

tested was quite effective in removing the coatings. (see Kevin Wanklyn's thesis for details.)

10. The jet-microcavitation combination is effective in removing surface coatings both in air and in underwater configurations. I.e. jet in air striking a sample held in air, or jet in water striking the sample held in water. The latter arrangement is simpler for first treating it with acoustic microcavitation.

• <u>Scale-up assessment of microcavitation for surface cleaning</u>

Before scale-up assessment is attempted it is critical that the phenomenon be first physically realized, and demonstrated repeatedly and conclusively at any scale at all. Once the proof of occurrence has been fully established, then one conducts a feasibility analysis to address several points of practicality: can the set-up be replicated easily and reliably with components available with the given state of the technology? Is it economical to do so? how efficient is the process? Feasibility follows the actual characterizing of the process, and then comes the task of scale-up assessment: What is the desired scaled up performance? How would one move from the table-top demonstration device to the operational model? Does the present state of knowledge and the state of the technology allow the making of the scaled up device? What are the implications to cost, utility, skills for use, safety and durability? Can it be embedded in the incumbent technology, and in current infrastructure? These questions are answered below based on the work done during this project.

1. By now we have clearly established that appropriately configured ACIM acoustic fields in a water like medium can remove surface coatings. We have removed various coatings of widely varying bonding strengths, from ink on Xerox prints, to all types of paint samples, rusted particulate coatings, and hard coatings on tools. In all cases the ACIM was able to remove the coating completely without damage to the substrate. If the ACIM field is strong then it could even be made to affect the substrate. However, the depth of removal can be as fine as several microns, and hence even a hard coating can be removed from a softer substrate without damaging the latter. The two student theses are replete with examples of demonstration of the ACIM effectiveness in coating

removal. The demonstration has be done in several set-ups with different geometries, and different transducers.

2. In the context of deinking, we have observed that impressive microcavitation effects are possible even with duty factors as low as 1%, i.e. the sound field was on for only 1% of the test duration. Typically few seconds are needed to effect spot deinking. This implies that the process is nearly spontaneous. Further, the acoustic powers involved are very minimal. Only a few milliwatts (estimated at 30 mW for deinking a focal spot of 6 mm^2) of acoustic power is needed to deink the small focal area. *Both these factors, near spontaneous processing time, low power requirement, indicate that scaled-up microcavitation implementation should be feasible.*

3. Concerning the efficiency of the process it should be remarked that cavitation is naturally a concentrator of energy. The energy soaked up during the expansion phase of the bubble is returned concentrated at the point of implosion during the collapse phase. Thus cavitation in general and ACIM in particular creates high energy densities at their points of implosion. There is no dispersive dissipation of energy as in explosions. Therefore if the ACIM event occurs in the close proximity of the coating to be removed it will deliver its blast directly to the coating. If cavitation occurs away from the coating surface then it will not do any decoating, for the effects of implosion are felt within a diameter or so of the imploding bubble. These considerations make microcavitation a highly efficient agency for delivering mechanical energy precisely at the point of use.

4. A key factor in establishing the scaleup capability of the process is the following: While we have established that the ACIM acoustic field does completely remove the coating in its focal spot because of the cavitation activity in the focal region, it is not, *a priori* clear if coating can be removed from the adjoining area, possibly by using another focussed ACIM system appropriately located. It is likely that cavitation which accounts for the fracturing of the liquid, might render the water fractured, thus precluding additional cavitation in the immediate vicinity. The only way to test this is to set-up the experiment using two transducers. It was observed that the two systems simultaneously bring about coating removal independently of each others presence. In fact a cylindrically segmented ACIM system with a line focus instead of the spot focus, worked quite well.

5. The previous results suggest arraying the transducers so that coating can be removed from larger areas. This array is certainly realizable given the current state of knowledge, and the level of technology. Transducer arrays have been used in sonar and diagnostic ultrasound, and the same might be conceived for the present coating removal task.

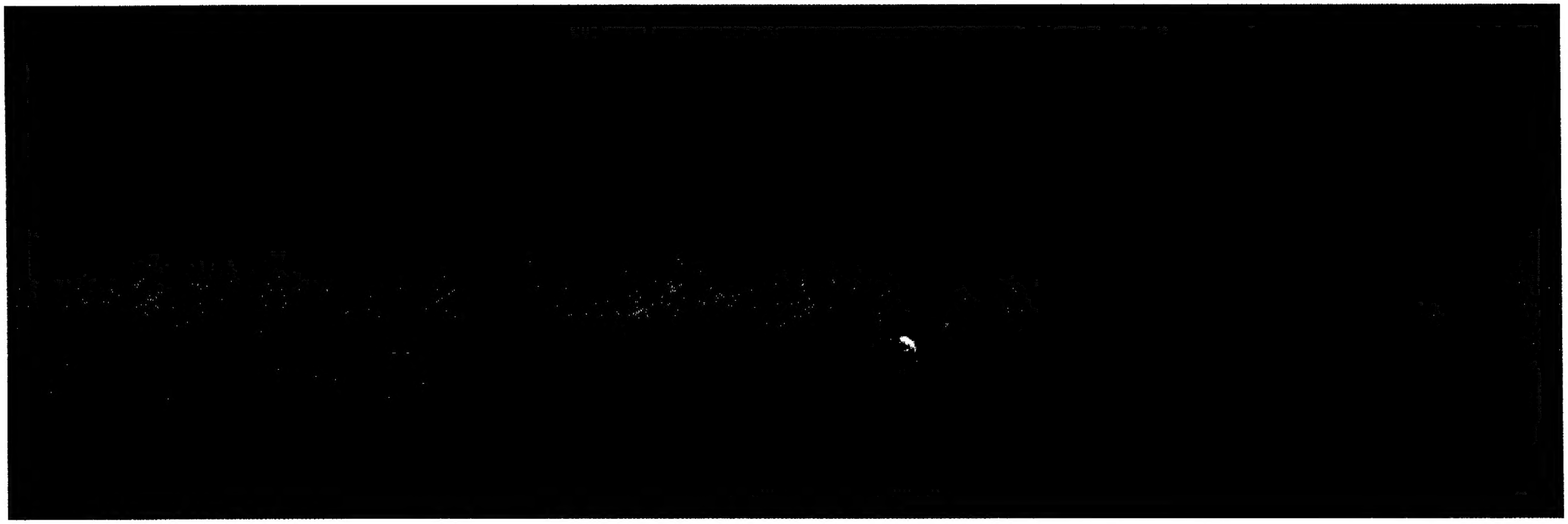
6. To be practical coating removal rates of around one square inch per minute would be desirable, and this is certainly achievable based on our work during this project. Our test systems can routinely remove around 5 mm^2 of coating within a millisecond, even while using a very small system and operating it at a duty cycle of mere 1% (i.e. the sound is off 99% of the time). It would be certainly worthwhile to build a transducer system for implementing the desired coating removal rate. Based on the powers used in the test setups, it would appear that in the scaled up device the powers involved would be not much more than several hundred watts. The physical size of the device would also not be unwieldy. In fact we did build a system by ACIM-adapting a standard power washer for use in coating removal.

- Setting up infrastructure of researching ACIM

A new 5000 Sq. ft lab space was developed during this project, explicitly for creating a research facility for investigating Acoustic Coaxing Induced Microcavitation. Here we can now design, build, test operate high intensity acoustic transducer systems. A very reliable calibration facility has been developed. In addition to mapping the acoustic fields involved, we can calibrate rapidly fluctuating pressure fields quite robustly, for example, we can measure pressure excursions both positive and negative with amplitudes exceeding 50 atmospheres and varying faster than a million times a second. In order to calibrate the devices we build, we have a implemented a novel radiation force balance that uses the second order field effect of radiation force to evaluate the pressures. A fairly large ultrapure water facility is also established. It is capable of providing 100 gallons per day of 18.2 Megaohm-cm water filtered to 0.2μm. Such clean water is critical for microcavitation research. Note that for the purpose of doing coating removal in the field, one could use any ordinary water; clean water is essential only for bench marking the process during research. In

Removal of Paint from a Surface

a typical sample



The above photograph shows an ACIM depainted path. The substrate is 7075-T6 aluminum. It was coated with one coat of Rust-oleum Hard Hat primer and two coats of Rust-oleum Hard Hat paint. The ACIM had a frequency of 1.06 MHz and a duty cycle of 1%. The aluminum substrate was not damaged during the process.

addition to these unique facilities, the lab has all the necessary electronic instrumentation, computers, mechanical and electronic bench-facilities, and a good imaging system to visualize the ACIM effects that occur in milliseconds. This would be a very useful lab for training both graduate students and undergraduates in the methods of underwater ultrasonics, more broadly physical acoustics.

• Training and encouraging at least two graduates to be entrepreneurs willing to pursue ACIM technology

Dr. Jogesh Chandran worked as a postdoc on this project for the first six months. He then left to take up a senior engineer position with Midwest Engineers in Chicago. Hang Ji completed is doctoral dissertation in Feb 2002: "Investigating Microcavitation in Bulk and on Surfaces". Kevin Wanklyn completed is MS thesis in Dec 2002: "A Study of Microcavitation at Surfaces". Bingrong He is a doctoral student who is continuing to work on cavitation on surfaces. Two mechanical engineering undergraduates, Michael Cochran and Travis Horsham, have been working in the lab on paint removal projects all throughout the duration of this project. Both Hang Ji and Kevin Wanklyn are working for a small start-up company, Uncopiers, Inc. which might be exploring to build tools for surface coating removal.

A brisk REVIEW of CAVITATION

Cavitation is a fascinating phenomenon. It can erode metallic surfaces, help shatter kidney stones, accelerate chemical reactions and even lead to light production — sonoluminescence, in the case of acoustic cavitation. Acoustic cavitation has been exhaustively reviewed by Flynn (1964), Neppiras (1979), Apfel (1981) and Prosperetti (1986). We will not dwell on the details of bubble dynamics, but we will recollect in simple terms the concepts of **rectified diffusion, resonance and transient cavitation.**

Consider a free bubble in the path of a sound wave. The bubble expands and contracts in response to the pressure alternations of the sound wave; the energy stored during the expansion being returned concentrated during the possibly implosive collapse. Should a bubble grow to two and a half times its original size during the negative excursion of the acoustic pressure then during the following positive half cycle its collapse speeds could become supersonic (Lauterborn, 1969). Such, almost single cycle violent events, called **transient cavitation**, may explain the energetic manifestations of cavitation.

Unlike the dramatic bubble growth within a single acoustic cycle as seen in transient cavitation, there exists a more gradual process, termed **rectified diffusion**. Under favorable conditions, a small bubble when exposed to a continuous sound wave tends to grow in size if rectified diffusion is dominant. According to Henry's law, for a gas soluble in liquid, the equilibrium concentration of the dissolved gas in the liquid is directly proportional to the partial pressure of the gas above the liquid surface, the constant of proportionality being a function of temperature only. When a bubble expands the pressure in the bubble interior falls and gas diffuses into the bubble from the surrounding liquid. When the bubble contracts the pressure in the interior increases and the gas diffuses into solution in the surrounding liquid. However,

the area available for diffusion is larger in the expansion mode than in the contraction mode, consequently there is a net diffusion of the gas into the bubble from the surrounding liquid over a complete cycle and thus the bubble grows due to rectified diffusion.

A bubble, however, can grow only up to a critical size — the **resonance radius** corresponding to the frequency of the impressed sound wave. For small amplitudes of oscillations a bubble acts like a simple linear oscillator of mass equal to the virtual mass of the pulsating sphere, which is three times the displaced volume of the fluid, and stiffness primarily given by the internal pressure of the bubble. (Surface tension effects are significant for small bubbles.) Following Minnaert (1933), ignoring surface tension effects, we have a simple relation for the resonance radius of air bubbles in water:

(Resonance radius in μm) x (insonification frequency in MHz) = 3.2

The above relation is valid to within 5% even for bubbles of radius 10μm. The bubble response becomes increasingly vigorous at resonance radius, limited by the damping mechanisms in the bubble environment — viscous damping, acoustic radiation damping and thermal damping. A post resonance bubble may exhibit nonlinear modes of oscillations or become transient if the forcing acoustic pressure amplitude is adequately high.

The above discussion presupposes the presence of a free bubble in the path of a sound wave. However, free bubbles do not last long in a body of water. The larger ones are rapidly removed due to buoyancy and the smaller ones dissolve even in slightly undersaturated water. While a 10 μm air bubble rises in water at a terminal speed of 300μm/s, it can survive for about five seconds before dissolving completely. The dissolution of bubbles is driven essentially by the excess pressure inside the bubble due to the surface tension.

It is very difficult to cavitate clean liquids. A pure liquid purged of all particulate impurities and stored in a perfectly smooth container can attain its theoretical tensile strength before undergoing cavitation or fracture. Under ideal conditions water can be as strong as aluminum; the tensile strength of water based on the homogeneous nucleation theory exceeds 1000 bars. (In cavitation studies tensile strengths are often quoted in terms of negative pressures, and threshold is understood as the pressure amplitude at which the first occurrence of cavitation is detected.) The observed strengths (thresholds) in practice, however, are very much lower, rarely exceeding a few bars for reasonably clean liquids. This is because there exist gas pockets within the liquid which provide the necessary seeding for cavitation. A gas site is often stabilized in a crevice (Harvey *et al.*,1944), either in the container wall or on a fluid-borne particle. Incomplete wetting traps gas at the root of a sharp crevice, stabilizing it against dissolution. Unlike a free bubble, surface tension in this case acts on a meniscus which is concave towards the liquid. Over-pressuring the liquid prior to insonification can force the meniscus further into the crevice and may bring about full wetting of the crevice, which then gives rise to increased thresholds.

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